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TECHNICAL REPORT RD-WS-92-3

AN ANALYSIS OF OBLIQUE COLLIMATORS WITH AXISYMMETRIC MIRRORS

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Research, Development, and Engineering Center

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Redstone Arsenal, Alabama 35898-5000

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A large-diameter collimator for providing a target at optical infinity to assess the tracking ability of an infrared seeker, was built in this laboratory using less expensive optics than the commonly used collimators. Most commercially manufactured reflecting collimators are difficult to make, extremely expensive, and usually small in diameter. The need for this large-diameter collimator led to an analysis of the off-axis aberrations of commonly used, commercially available mirrors. This report provides an analysis of the performance of simple spherical mirrors, and compares their performance to that of mirrors of other axisymmetric figures.

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I. INTRODUCTION

Reflecting collimators are commonly used as alignment tools for infrared systems because common glasses have very poor transmission at infrared wavelengths. Many of the infrared transmitting materials are opaque at visible wavelengths, making the initial setup very awkward. Most reflecting collimators use off–axis parabolic mirrors to provide a diffraction–limited plane wavefront. Such mirrors are difficult to make, extremely expensive, and usually rather small in diameter. Fortunately, such pristine performance is not always required, and a large output beam is much more important.

In this laboratory, a large–diameter collimator is needed to provide a target at optical infinity to assess the tracking ability of an infrared seeker. Since diffraction–limited performance is not a requirement and a large output beam is needed, it seemed desirable to build a collimator using less expensive optics. This requirement has led to an analysis of the off–axis aberrations of commonly available mirrors.

The purpose of this report is to provide an analysis of the performance of simple spherical mirrors and to compare their performance to that of mirrors of other axisymmetric figures. Third order aberration formulae and spot diagrams obtained by ray tracing are given.

II. ABERRATIONS OF AN OPTICAL SURFACE

Since we are using axisymmetric mirrors in an off–axis mode, the off–axis aberrations will be dominant. Spherical aberration is insignificant by comparison. The principal aberrations are third–order astigmatism and coma.

Third order aberrations are computed by tracing an axial ray from the axial intercept of the object through the rim of the entrance pupil, and a principal ray from the edge of the object through the center of the entrance pupil. Both rays are taken as paraxial rays.

Having traced these rays from the object–plane to the image–plane, the *optical invariant I*, is determined by the formula

$$I = y_p N u - y N u_p, \tag{1}$$

where

y = ray height at the surface,
N = index of refraction preceding the surface,
u = the slope of the ray.

Subscripted and unsubscripted letters refer to the principal ray and the axial ray, respectively. The intersection of the principal ray with the image plane is given by

$$h = \frac{I}{N'u'}, \tag{2}$$

where N' and u' are the index and slope of the axial ray after reflection from the mirror. N and u' are positive, and N' and u are negative in this system.

It can be shown that the aberrational contributions of a spherical surface are given by the following expressions:

$$SAC = Bi^2h, \tag{3}$$

$$SCC = Bii_ph, \tag{4}$$

$$TAC = Bi_p^2h, \tag{5}$$

where

SAC = spherical aberration contribution,

SCC = sagittal coma contribution,

TAC = transverse astigmatism contribution,

$$i = cy - u, \tag{6}$$

$$i_p = cy_p - u_p, \tag{7}$$

$$B = \frac{N(N' - N)}{2N'I} y (u' - i). \tag{8}$$

Smith [1] has shown that these formulae can be reduced to a more convenient form, giving the blur diameters for the various aberrations. The sum of the blur diameters resulting from spherical aberration, coma, and astigmatism will yield a conservative (i.e., large) estimate of the total blur. The angular blurs for a spherical mirror are given below in radians.

$$SAC = \frac{0.0078}{(f/\#)^3}, \tag{9}$$

$$SCC = \frac{(1_p - R)\, U_p}{16R\, (f/\#)^2}, \tag{10}$$

$$TAC = \frac{(1_p - R)^2 U_p^2}{2R^2\, (f/\#)}, \tag{11}$$

where

l_p = mirror to stop distance,

R = mirror radius of curvature,

U_p = half–field angle in radians.

Here we assume that the object is at infinity. If the total aberrational blur is determined by summing the above expressions, the calculations will yield a result which is larger than is required in practical circumstances. This is because the energy distribution within the blur is not taken into account. The outer regions of the blur may be so faint that they are of no practical consequence. For most practical purposes, the "hard core" focus is much more relevant.

If one has access to computer software for optical ray–tracing, the most convenient means of ascertaining the total blur and its intensity distribution is a "spot diagram". This has the advantage of accounting for all higher–order aberrations. Determining these aberrations analytically from paraxial ray traces is an extremely laborious task.

III. SPOT–DIAGRAM ANALYSIS

Beam 3™ [2] optical ray–tracing software was used in preparing the spot diagrams for the analysis of the performance of the simplified oblique collimators. This software uses a Monte Carlo random ray generator to initiate, in this case, a collimated ray bundle filling the entrance pupil of the collimator. The entrance pupil was taken to be the mirror itself. The rays were traced through the system to a pinhole light source. The rays were traced through the system backward because this allowed a single initial ray bundle to be used for all the focal lengths and mirror tilts that were to be studied. The linear spread of the ray bundle was then converted into an angular aberration through division by the focal length of the mirror. This gives the tangent of the angular spread. Since this angle is very small, it is taken to be equal to the angle in radians. The optical arrangement is shown in Figure 1.

A Gauss–Newton nonlinear iterative least–squares routine was used to optimize the focus and the tilt of the mirror. The criterion used in the optimization was a minimum rms distribution of the rays in the focal plane. Three focal ratios were used; f/5, f/7.5, and f/10. It was felt that a focal ratio shorter than f/5 would exhibit too much aberration for general use, while a focal ratio longer than f/10 would cause the instrument to be inordinately long.

The optimized focus was found, utilizing the full aperture of the mirror. For comparison purposes, the spot diagrams for the spherical mirrors were compared with those for parabolic mirrors and with those for mirrors having an optimized figure. All mirrors considered have axial symmetry. The spot diagrams for the full apertures are shown in Figure 2. The optimized figure was found to depend very strongly on the arrangement of the parallel bundle of rays passing through the entrance pupil. The optimum figure was found to range from an oblate spheroid (conic constant > 1) to a hyperboloid (conic constant < 0). This suggests that the spherical aberration is insignificant in comparison to the off–axis aberrations. If off–axis mirrors are not going to be used, spherical and parabolic mirrors (conic constants of 1 and 0, respectively) will work as well as any, and both types are relatively inexpensive.

In all figures in this report, the mirrors are tilted at the proper angle to place the pinhole light source at a location one fourth of the mirror diameter outside the collimated beam. This allows the beam to be completely unobstructed.

Figure 3 illustrates the effect of increasing the focal ratio of a tilted spherical mirror. Note that in the longer focal ratios, virtually the entire aperture could be used in conjunction with an optical system having a resolution of 0.2 milliradians. The focus has been adjusted to provide maximum uniformity of performance over the entire aperture.

The mirrors are not as bad as they appear in the full–aperture spot diagrams. A collimator should be designed to over fill the aperture of the receiving optical system. In the case of a tracking system having articulated optics, the output beam from the collimator should be considerably larger than the tracker's optical system. The aberrational spread within this small portion of the total collimated beam will be much less than that of the whole beam. Therefore, smaller apertures were used to sample the collimated beam at several locations within its cross section. The sampling areas are shown in Figure 4. It should be noted that it is not necessary to sample the beam on both sides of the (Y, Z) plane, since the aberrational spreads on each side of this plane are simply mirror images of one another.

Because the best focus for a reduced aperture is dependent on the region of the beam sampled, the calculated focus was changed to make the beam quality more uniform over the cross–section of the beam. Figure 5 shows the focus error in the plane of the mirror tilt. The ray height at the nominal focal plane is plotted versus the slope of the ray. If the focus was constant across the diameter, the diagram would consist of a single horizontal line.

The focus having been adjusted, the beam is now sampled at the positions shown in Figure 4, with an aperture mask having an opening 0.25 times the aperture of the mirror. Figures 6, 7, and 8 show the aberrational spreads within the output beams of F/5, F/7.5, and F/10 systems, respectively. A spherical mirror is used in each case.

Figures 9, 10, and 11 are similar to Figures 6, 7, and 8, except the opening in the aperture mask is reduced to 0.1 times the mirror aperture.

IV. CONCLUSIONS

It is evident from this analysis that simple, inexpensive mirrors may be used in an oblique, Hershelian arrangement in the construction of collimators for use with low–resolution optical systems. Illuminators for articulated guidance systems fall well within this category. Spherical mirrors, or even parabolic telescope mirrors, can be used provided the focal ratio is not made too short. There is no need to use an optimized figure since this figure is so dependent on the orientation of the sampling rays used in its calculation. At best, the improvement in the performance would be very slight. Actually, this figure is only a mathematical artifact of the ray geometry.

Although these mirrors perform well in low–resolution systems, off–axis parabolic mirrors are needed for any high–resolution applications. Spherical mirrors might suffice if they are made in a very long focal ratio. Proper application of simplified optical systems can provide a considerable reduction in the cost of the instrumentation.

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2. Beam 3 Optical Ray Tracer, Stellar Software, Berkley, CA, 1989.

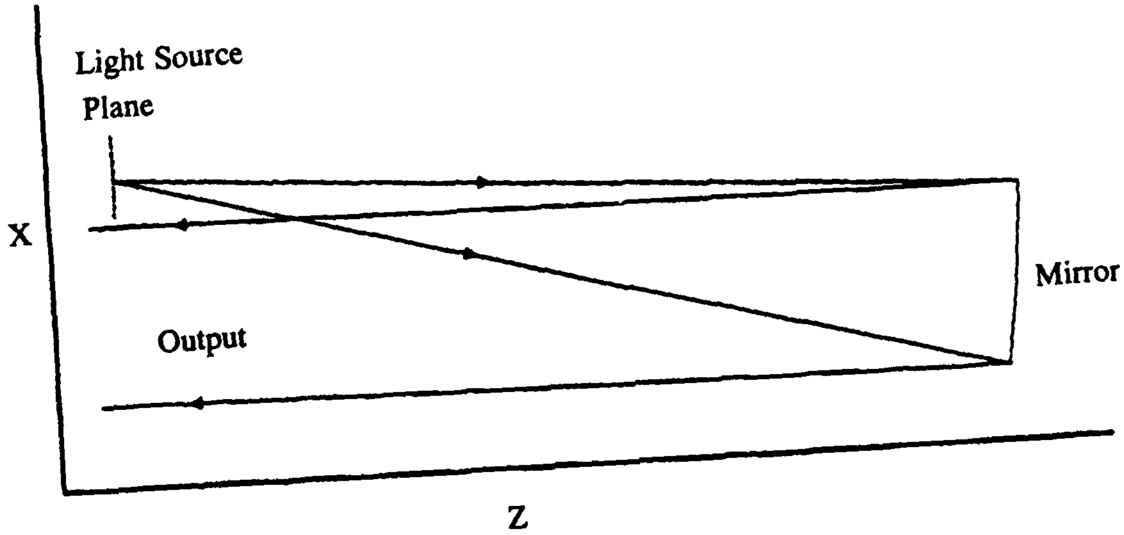


Figure 1. Optical Layout of Oblique Collimator

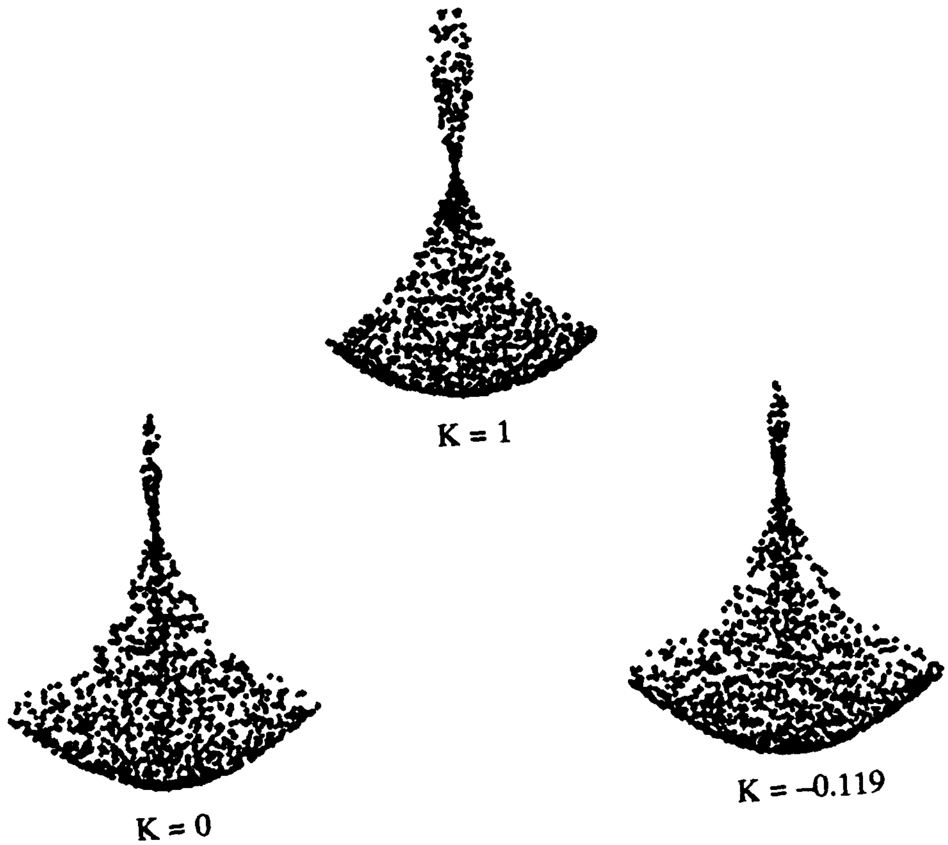


Figure 2. Full Aperture Spot Diagrams for Mirrors of Conic Constant K

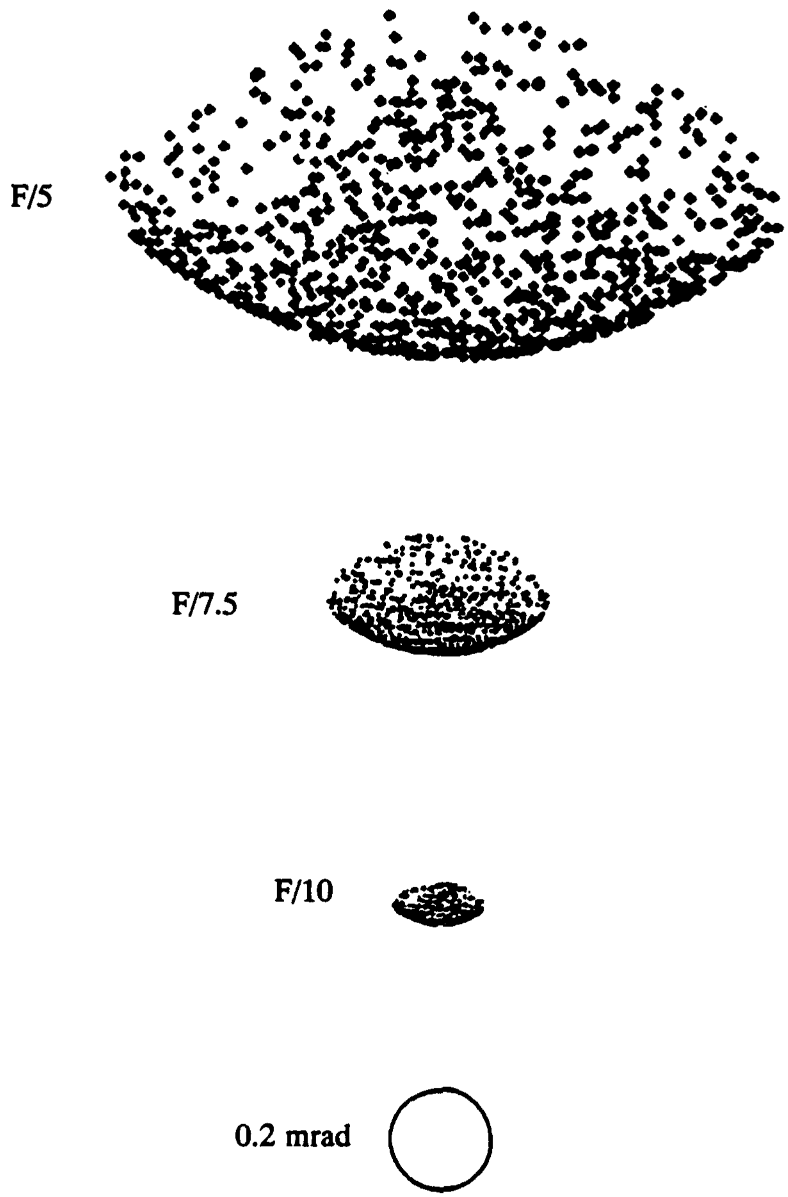


Figure 3. Aberrational Spread of Tilted Spherical Mirrors

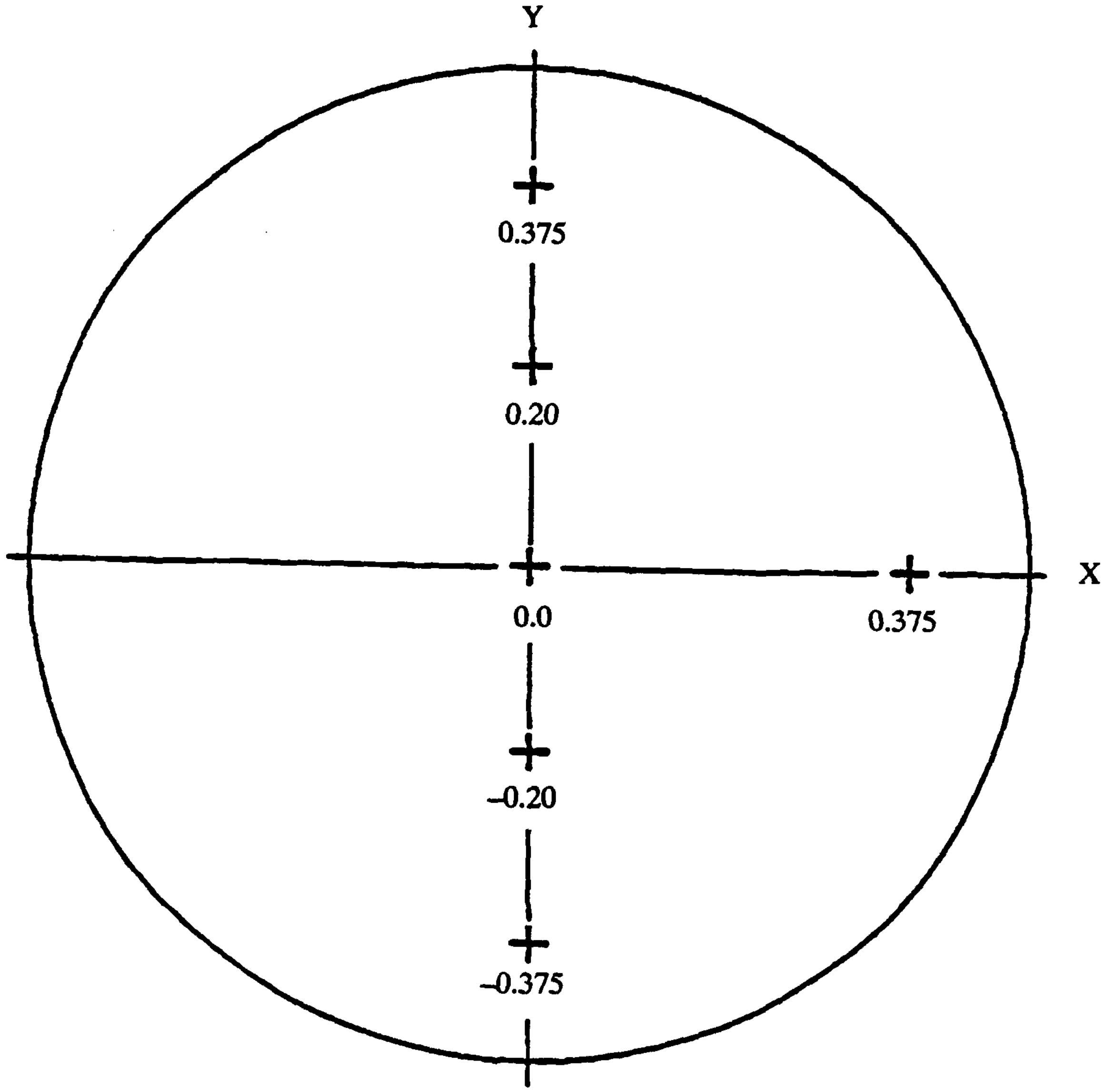
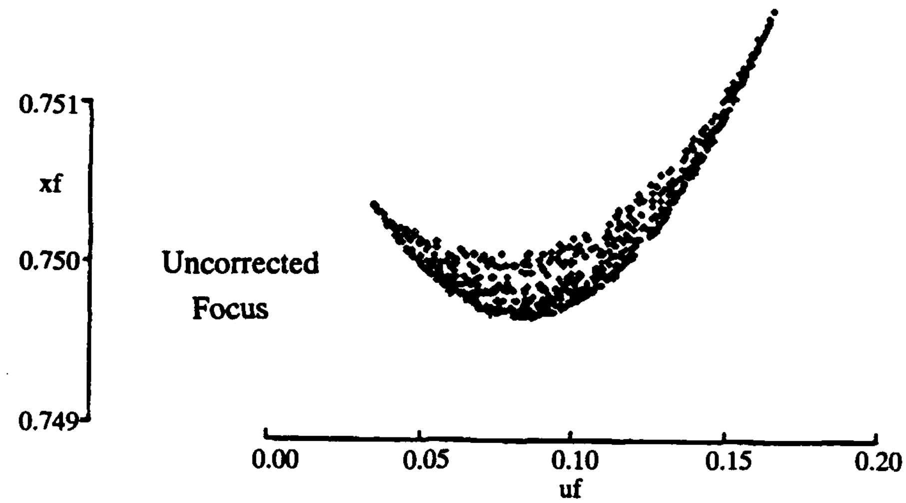


Figure 4. Sampling Areas Within the Collimator Output Beam



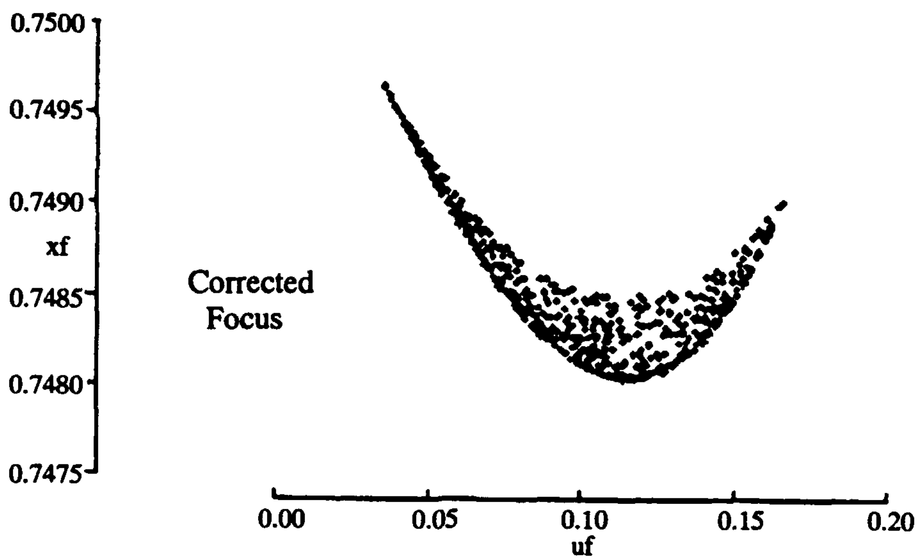


Figure 5. Focus Plot Across the Beam Diameter in the Tilt Plane

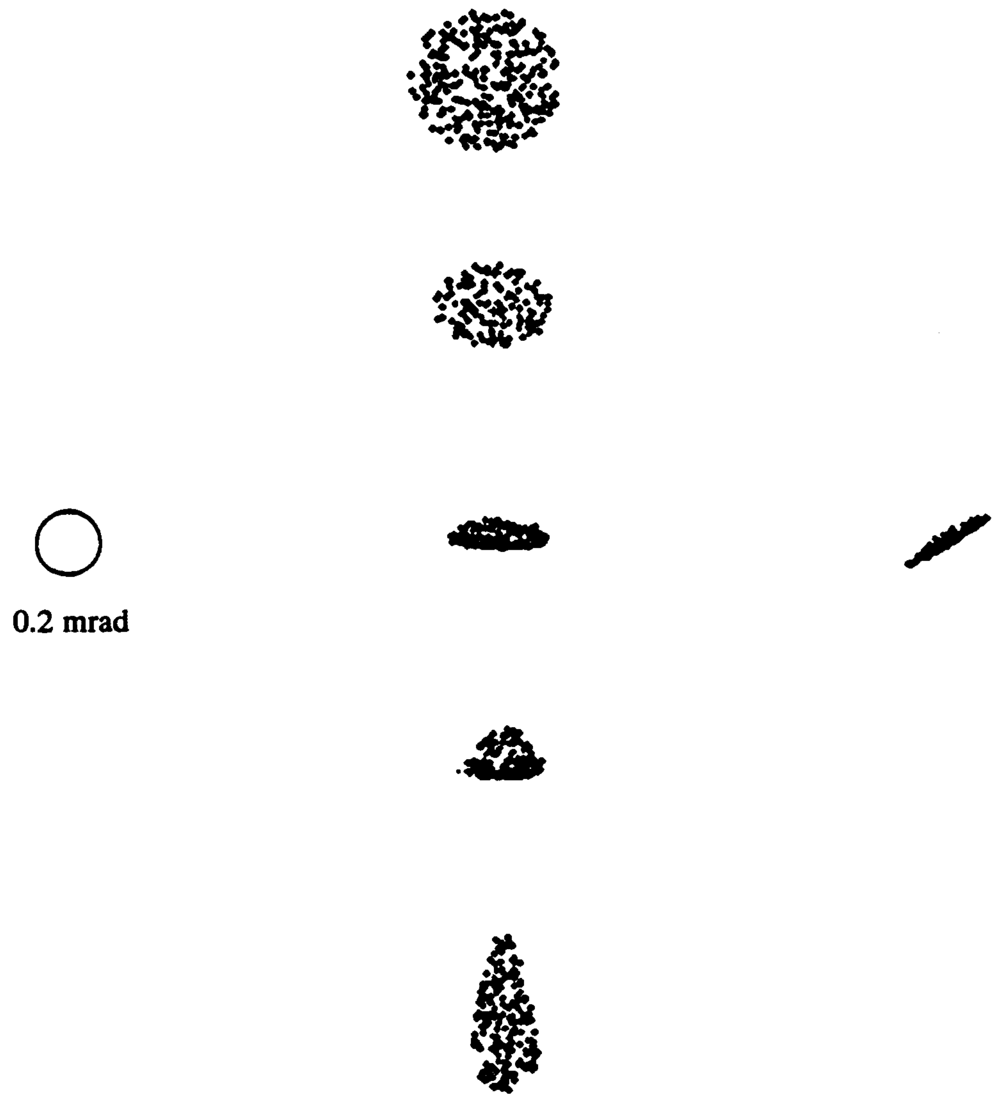


Figure 6. Aberrations in the Output Beam of an F/5 Collimator with a 1/4 Mask

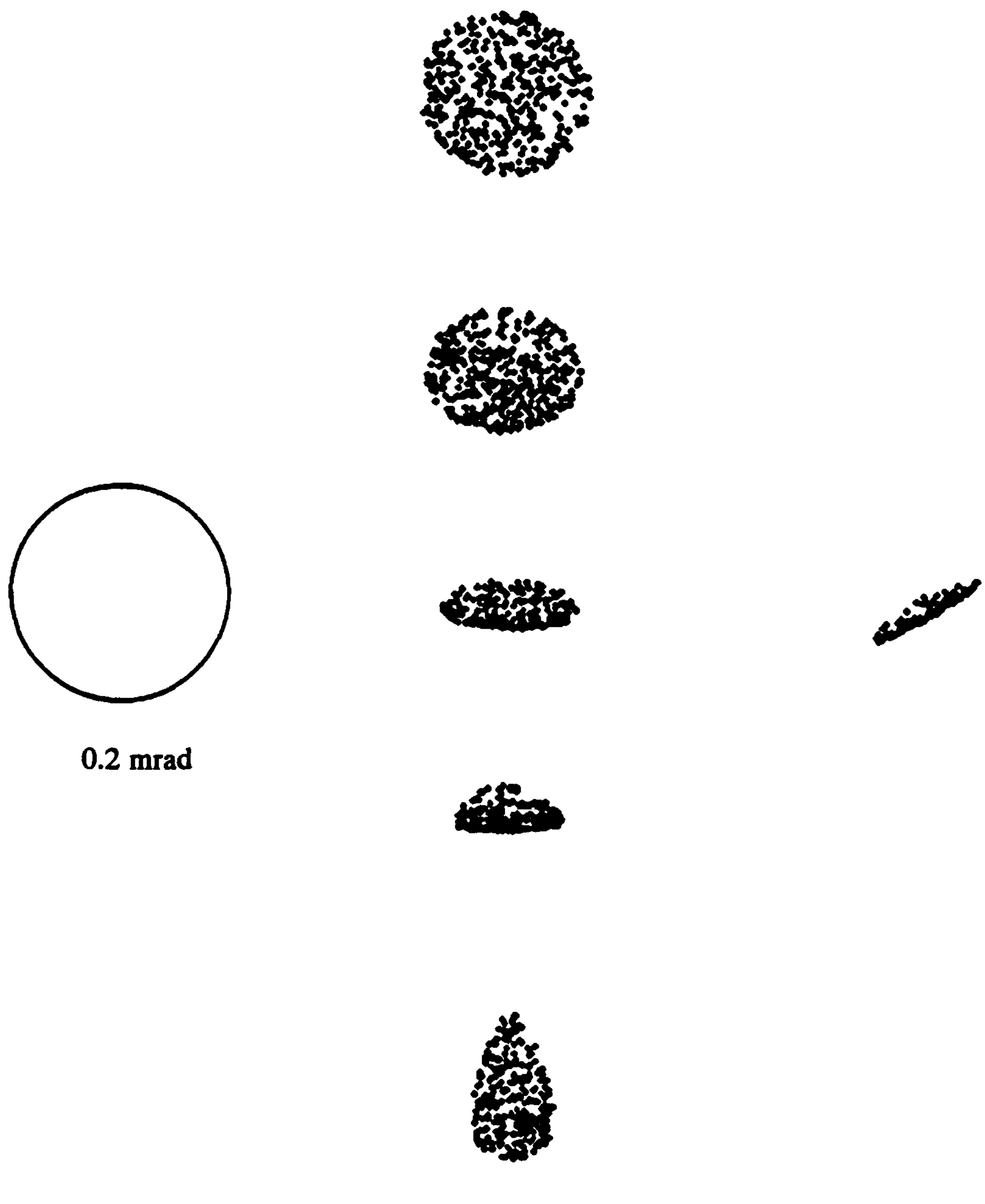


Figure 7. Aberrations in the Output Beam of an F/7.5 Collimator with a 1/4 Mask

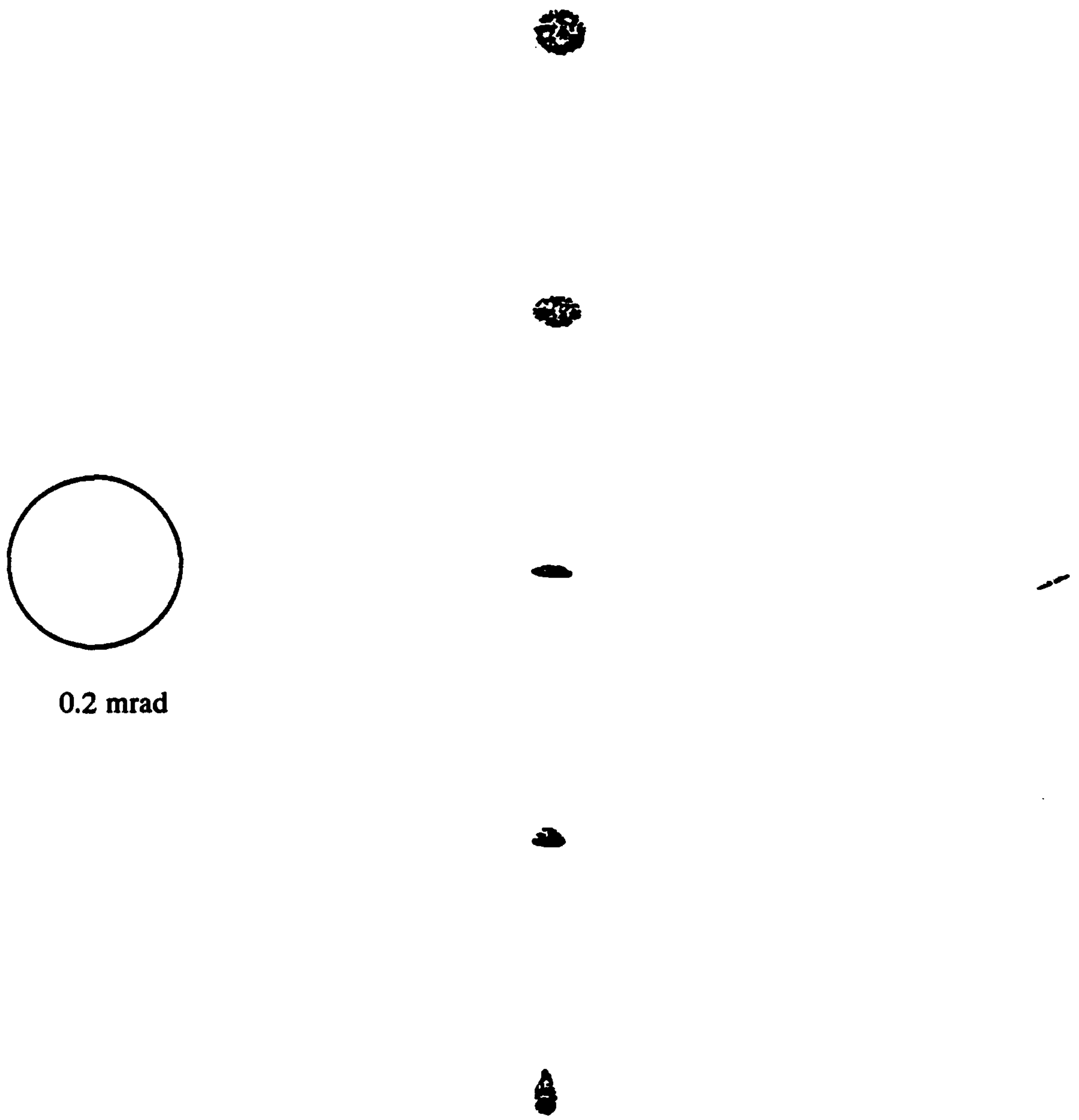


Figure 8. Aberrations in the Output Beam of an F/10 Collimator with a 1/4 Mask

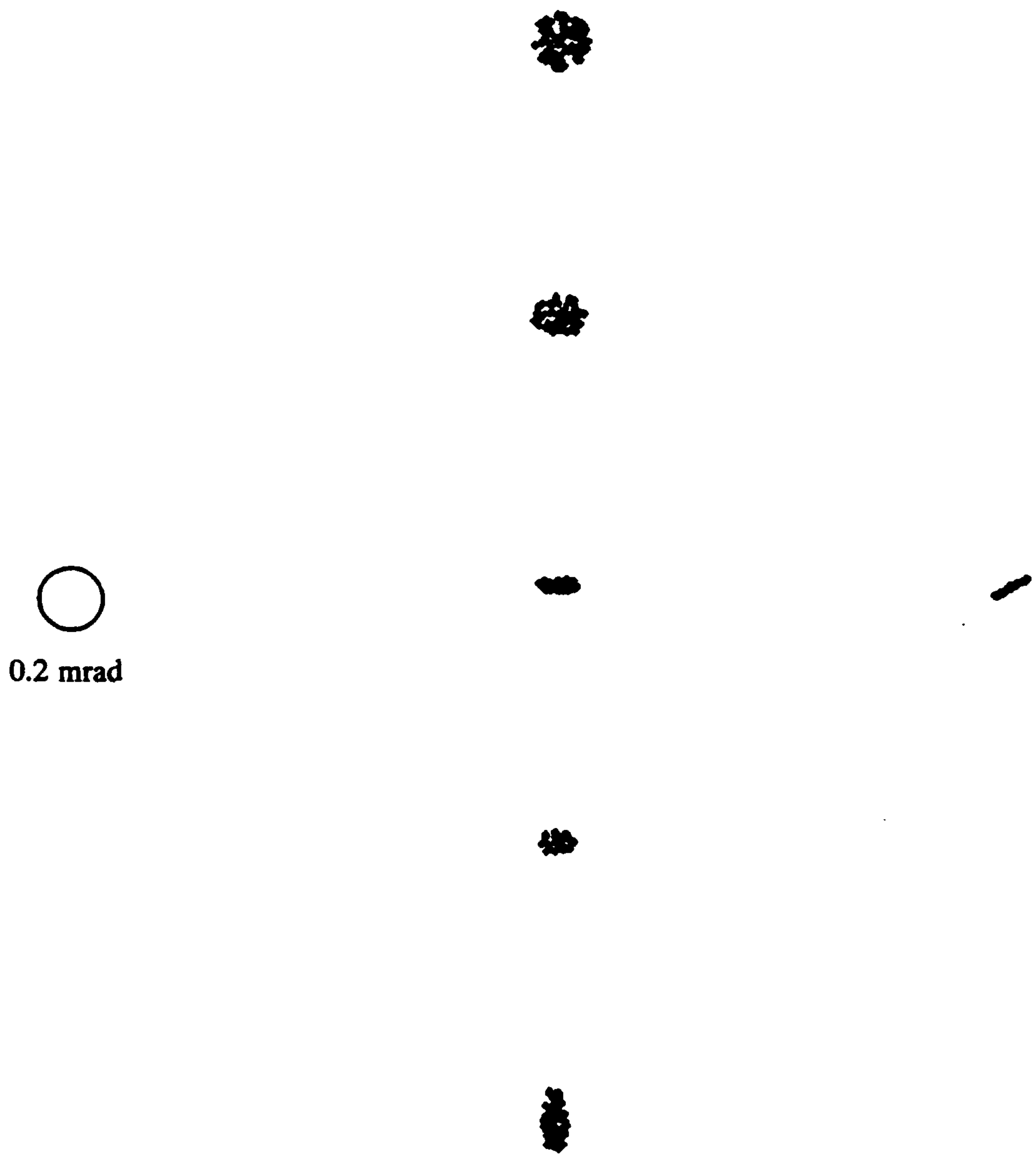


Figure 9. Aberrations in the Output Beam of an F/5 Collimator with a 1/10 Mask

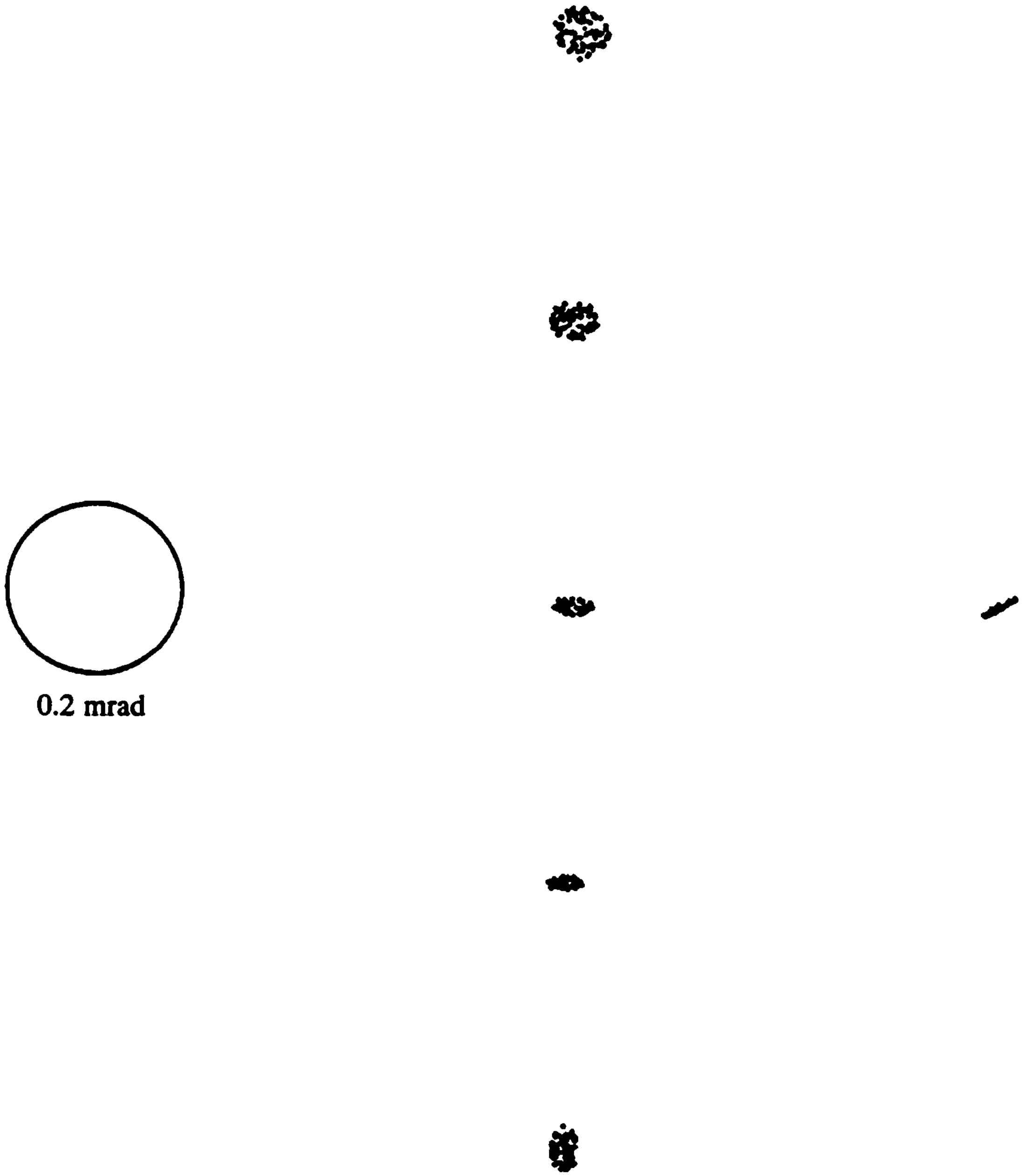


Figure 10. Aberrations in the Output Beam of an F/7.5 Collimator with a 1/10 Mask

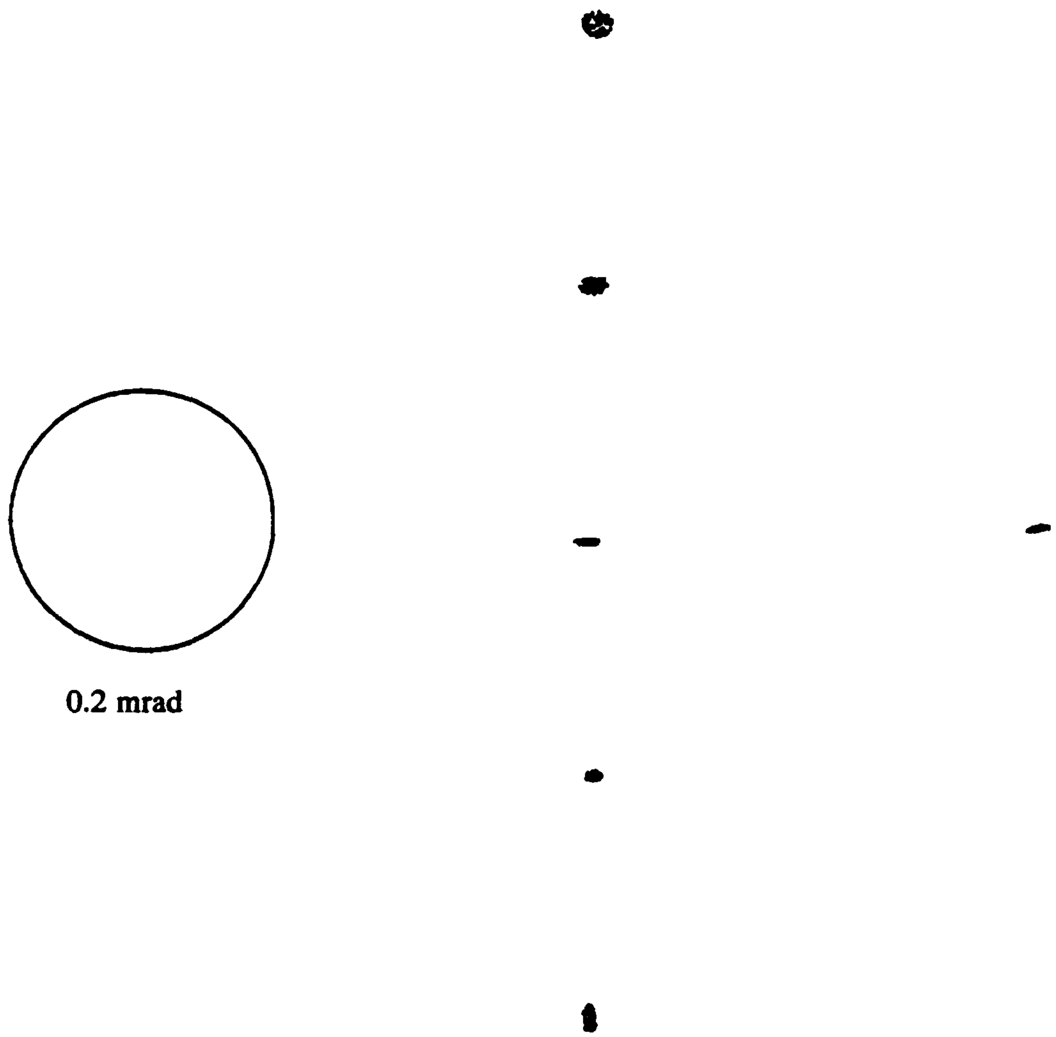


Figure 11. Aberrations in the Output Beam of an F/10 Collimator with a 1/10 Mask

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